

# **A characterization of the Equatorial Undercurrent between 92°00'W and 91°20'W**

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Running Title: The EUC Between 92°00'W and 91°20'W

## NON-TECHNICAL SUMMARY

The Equatorial Undercurrent (EUC) flows from the western Pacific Ocean to the eastern Pacific Ocean within two latitudinal degrees of the equator. The EUC forms because predominantly westward winds near the equator create westward surface currents resulting in the formation of a shallow yet broad 'pile' of water on the order of 70 centimeters above average sea level in the western Pacific Ocean. Since there is no Coriolis force at the equator, the EUC forms to partially counteract the effects of the westward wind, 'draining' some of this 'piled' water eastward along the equator beneath the westward surface currents. The Galápagos Islands exist on and near the equator in the eastern Pacific and thus represent an obstruction to the EUC. Historical observations have found that much of the EUC splits into two branches to circumnavigate the archipelago, one traveling around the northern reach and the other flowing to the south of Isabela Island. In addition to these horizontal deflections, some of the EUC is forced upward and some is forced downward. The upwelling is of tremendous biological importance because it brings nutrients to the surface where photosynthesis can occur. In addition to the higher concentration of chlorophyll at the surface, the upwelled masses of the EUC are detectable at the surface as regions of lower temperature because EUC water is colder than the surface water. During January 2006, this study examines how the EUC was disrupted by the western portion of the Galápagos Islands using an Acoustic Doppler Current Profiler (ADCP), deployed drifters, and discrete water sampling. Along 92°W, the EUC occurred at an average depth of about 100 meters. The EUC flow around the northern portion of the Galápagos was much greater than flow to the south.

## ACKNOWLEDGMENTS

Dr. Seelye Martin has been an outstanding guide and mentor throughout this learning experience. I am grateful to the teaching team, especially Llyd Wells, the US Navy, the *R/V Thompson* crew, and my OCEAN 444 peers. I also thank Robert Drucker and Stephen C. Riser for providing software and hardware support, and Professor Roy Carpenter for working through logistics that has given UW students the opportunity to study oceanography while in the Galápagos Islands.

## ABSTRACT

The EUC exhibits seasonality and interannual variations, is important to regional biological activity as well as global climate, but its termination and subsequent distribution is still relatively underdocumented. Interest in these various aspects of the EUC and access to a hull-mounted ADCP, ARGOS and Iridium drifters, CTD, and satellite data allowed for a characterization of the EUC upon its approach to the Galápagos Archipelago. The EUC was found between depths of 28 to about 212 m, had eastward flow as far south as  $0.8^{\circ}\text{S}$ , and exhibited prominent flow around the northern portion of Isabela Island. Maximum velocities were found between depths of 60 to 76 m and between  $0.1^{\circ}\text{N}$  and  $0.5^{\circ}\text{N}$ . These were oriented northeastward, had a speed of about  $80 \text{ cm s}^{-1}$ . CTD casts confirmed that the saline and thermal properties of the EUC agreed with historical data.

## INTRODUCTION

Roughly speaking, the EUC is a subsurface current about 200 meters thick with typically maximal eastward velocities at a depth of 75 meters (Feldman 1984). Though the vast majority of the EUC remains subsurface along the western margins of the Galápagos Archipelago, the presence of nutrient-rich upwelled EUC waters is of tremendous biological importance (Feldman 1984). Among the determinants of the location and magnitude of the EUC are seasonal and interannual variations in wind stress, strength of neighboring or adjacent currents, and geostrophic forcings (Cane 1979, Enfield 1981). The EUC has three distinctive hydrographic features (Lukas 1986): (1) a 13°C-14°C thermostad (region of uniform temperature), (2) a high salinity core (34.95-35.20 PSU), and (3) a high dissolved oxygen concentration tongue which decreases at the 100 meter depth from 2.3 ml l<sup>-1</sup> along 98°W to 1.8 ml l<sup>-1</sup> at 82°W. The thermostad is thickest slightly south of the equator while west of the Galápagos , and is poorly developed along the equator east of the Galápagos , apparently due to convergence with the Southern Subsurface Countercurrent (Lukas 1986). The southward projecting branch of the EUC experiences rapid decreases in dissolved oxygen (Lukas 1986).

Though some meridional fluctuations are evident, once formed, the eastward propagation of the EUC west of the Galápagos is constricted to within two degrees latitude of the equator and exists at depths between 50 and 275 meters (Steger 1998). Upon approaching the Galápagos, Lukas (1986) and Steger (1998) found that at the time of their observations, the core of the EUC (highest flow velocities and deepest subsurface extent) were centered approximately 0.5 degrees south of the equator. Since the Galápagos Archipelago extends roughly from 0.5°N to 1.0°S, it represents an obstacle to the eastward propagation of the EUC. The collision of the EUC flow against the Galápagos Archipelago results in a combination of five subsequent flows along the steep

western bathymetry of Isabela and Fernandina Islands: 1) some is upwelled, 2) some is downwelled, 3) some is deflected around the northern perimeter of Isabela Island, 4) some is deflected around the southern perimeter of Isabela Island, and 5) some of the EUC waters are recirculated in and out of the EUC (Fig. 2). As reviewed by Steger (1998), several studies have concluded that although most of the EUC flow is around northern Isabela (Knauss 1966, Chistensen 1971, Pak and Zaneveld 1973), there is also evidence of significant southern flow (Wyrтки 1967, Lukas 1986).

Steger (1998) used ADCP and CTD data during 8-21 November 1993 to investigate circulations around the Galápagos Islands and found that the westward flowing South Equatorial Current dominated the surface waters of the region save a small region west of Fernandina Island, where some shoaling of the EUC was observed. West of the Galápagos, he found the EUC centered along  $0.5^{\circ}\text{S}$  at 70 meters with maximum velocities of about  $0.6 \text{ ms}^{-1}$  and transporting 6.6 Sv along  $92^{\circ}\text{W}$ . In contrast to Knauss (1966), Christensen (1971) and Pak and Zaneveld (1973), Steger found strongest subsurface flow south of the equator, emphasizing the dynamic and variable nature of this current.

The goal of the study here was to determine the location and characteristics of the EUC west of the Galápagos in January 2006 while aboard the *R/V Thomas G. Thompson*, predominantly using the 75 MHz hull-mounted Acoustic Doppler Current Profiler (ADCP). The ADCP was programmed to use 50 intervals, referred to as bins of eight vertical meters to measure water velocities between water depths 20 and 420 m. Salinity, temperature, and dissolved oxygen were profiled along the ADCP transects between  $92^{\circ}00'\text{W}$  and  $91^{\circ}20'\text{W}$  for comparison to historical EUC data. ARGOS and Iridium Drifters were deployed at  $92.00^{\circ}\text{W}$  and  $1.5^{\circ}\text{S}$  and were parked for at depths of ##### meters, surface every ##### days, and have drifted west-north-westward from their

original deployment position. Four other drifters also provide physical and chemical information of the region, two of which had been deployed by a previous expedition, and two of which were deployed by fellow undergraduate physical oceanographer Xyrone Ocampo. These drifters will not be used to evaluate the subsequent paths of the bifurcated EUC because they are beneath the EUC. However, these drifters can still identify the salinity and temperature signatures of the EUC as they (REFER TO) penetrates to the surface regularly. The top 20 meters of the water column could not be measured by the ADCP due to the turbulence induced by the ship during navigation. In regions with powerful currents, it is possible to gather reliable data while traveling at speeds of up to 12 knots. However, it is known that the accuracy of the data increases with slower ship speeds.

## METHODS

Discontinuous transects (to accommodate logistical constraints of the cruise) were undertaken along 92°W (Fig. 1) from January 13 to January 23 of 2006. The length of time between maneuvering away from the equator and 92°W and resuming a northward transect from that point was #####. The ADCP was activated and recording almost continuously throughout the duration of the OCEAN 444 data-collection expedition as the *R/V Thompson* navigated the Galápagos Archipelago. CTD casts at ##### stations (Fig. 1) profiled the water column to compare salinity, temperature, and dissolved oxygen values to the known signatures of the EUC. One ARGOS and three Iridium floats were also deployed. All ADCP, CTD, and drifter data were shared with the other physical oceanographic student Xyrone Ocampo. The dissolved oxygen readings from the instrument mounted on the CTD were calibrated by manually processing seawater samples collected with the CTD at various depths using the Winkler method (Codispoti 1998). Salinity readings from the conductivity apparatus of the CTD were calibrated by manually processing seawater samples collected with the CTD at various depths using a Portasal salinometer (model 8410).

To calibrate a hull-mounted ADCP, the ship must travel some distance (1 or 2 km) across non-turbulent, steady water flow, and then backtrack over the same transect to confirm that the readings are identical (assuming the water flow has not changes during that time) and to identify artifacts within the data that are due to GPS error, ship speed, and other possible sources of error. This calibration was skipped, primarily due to ship-time concerns.

Steger (1998) estimated alignment sensitivity errors following the method of Joyce (1989) to correct for ADCP error. A navigation misalignment of -0.85/360 was

identified for the data collected aboard the *R/V Thompson*, but correction for ADCP alignment error using Joyce (1989) has not been applied. VmDAS and WinADCP were used to export ADCP data to Matlab, which was used to plot horizontal velocities, one depth at a time, of various portions of the ship track simultaneously. Paintbrush was then used to paste images side-by side.

## RESULTS

Our transects along  $92^{\circ}\text{W}$  did not show any evidence of a portion of the EUC branching south of Isabela Island. Yet along the western coast of southern Isabela there is evidence of southeastward along-shore current between depths 20 to 84 meters. The southernmost eastward flow of the EUC along  $92^{\circ}\text{W}$  was measured at a depth of 68 meters at about  $0.78^{\circ}\text{S}$ . The northern extent of the EUC was not measured since it continued north of the ship track's northern-most reach which occurred at  $91.82^{\circ}\text{W}$  and  $1.01^{\circ}\text{N}$ . Maximum EUC speeds were found along  $92^{\circ}\text{W}$  between 60 and 76 m depths, were northeastward, and had magnitudes of about  $1.0\text{ ms}^{-1}$ . The EUC's maximum height was 192 meters: at  $0.15^{\circ}\text{N}$  it stretched from 28 m to almost 220 m. An EUC signal along the diagonal transect from  $92^{\circ}\text{W}$  and  $0.75^{\circ}\text{N}$  to Roca Redonda and Punta Albemarle was found between 92 and 188 meters, and though this was due west of the thickest and fastest EUC flow, the flow was relatively thin; the top surface of this 96 m thick flow of EUC was about 84 m below that thickest EUC signal, and the bottom surface of this thin flow was 24 m above the thickest EUC signal. Except for the water moving due east in bin three (44m), along the transect from  $1.26^{\circ}\text{S}$  and  $91.32^{\circ}\text{W}$  to  $1.26^{\circ}\text{S}$  and  $92^{\circ}\text{W}$ , at all other depths water is moving northwestward. Beneath the southeastward current along Isabela's southwestern shore, water seems to flow northwestward along the west coast between 84 m and the 420 m, which was as deep as ADCP measurements were made.

Though along  $92^{\circ}\text{W}$  northward flow was strongest at the surface, At 28 meters, surface flow south of the equator was notable northward. This region, between 44 and 76 meters expressed medium southwestward speed.

## CONCLUSIONS AND SUMMARY

During the 13 - 23 January 2006, the EUC was observed to have maximum velocities at depths of 60 to 76 m and between 0.1°N and 0.5°N, were oriented northeastward, and had a speed of about 80  $\text{cm s}^{-1}$ . At maximum thickness, the EUC was found between depths of 28 to about 212 m, and had eastward flow as far south as 0.8°S. Importantly, the vast majority of the EUC was deflected around the northern portion of Isabela Island and very little was deflected to the south. These CTD casts confirmed that the saline and thermal properties of the EUC agreed with historical data.

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Table 1: Drifter profile with EUC water pressure and temperature signatures

T	p	t	s	theta	sigma
6.9	21.255	34.438	21.254	23.9985	
10.7	18.771	34.766	18.769	24.9021	
20.4	18.145	34.783	18.141	25.0720	
30.6	16.666	35.005	16.661	25.5991	
39.9	15.347	35.072	15.341	25.9528	
50.2	15.100	35.118	15.092	26.0434	
60.0	14.240	35.036	14.231	26.1667	
69.9	13.987	35.016	13.977	26.2050	
78.1	13.751	34.994	13.740	26.2376	
90.1	13.695	34.985	13.682	26.2426	
100.5	13.646	34.981	13.632	26.2500	
110.0	13.605	34.976	13.589	26.2549	
120.3	13.578	34.972	13.561	26.2576	
130.4	13.529	34.967	13.511	26.2641	
140.1	13.440	34.955	13.420	26.2734	
150.0	13.367	34.948	13.346	26.2832	
160.2	13.328	34.944	13.306	26.2883	
169.8	13.316	34.944	13.292	26.2910	
180.1	13.309	34.944	13.284	26.2927	
190.3	13.300	34.944	13.273	26.2949	
200.3	13.293	34.944	13.265	26.2966	
210.1	13.300	34.947	13.271	26.2977	
220.5	13.256	34.947	13.225	26.3070	
229.7	13.219	34.945	13.187	26.3132	
239.9	13.161	34.937	13.128	26.3190	
250.4	12.840	34.919	12.806	26.3696	
260.3	12.667	34.906	12.632	26.3940	

270.4	12.370	34.887	12.334	26.4375
280.2	12.101	34.864	12.064	26.4717
290.1	11.625	34.836	11.588	26.5401
300.3	11.358	34.820	11.320	26.5774

Figure 1: Leg 1 and Leg 2 ADCP transects

TN189 Cruise Track (Leg-1)

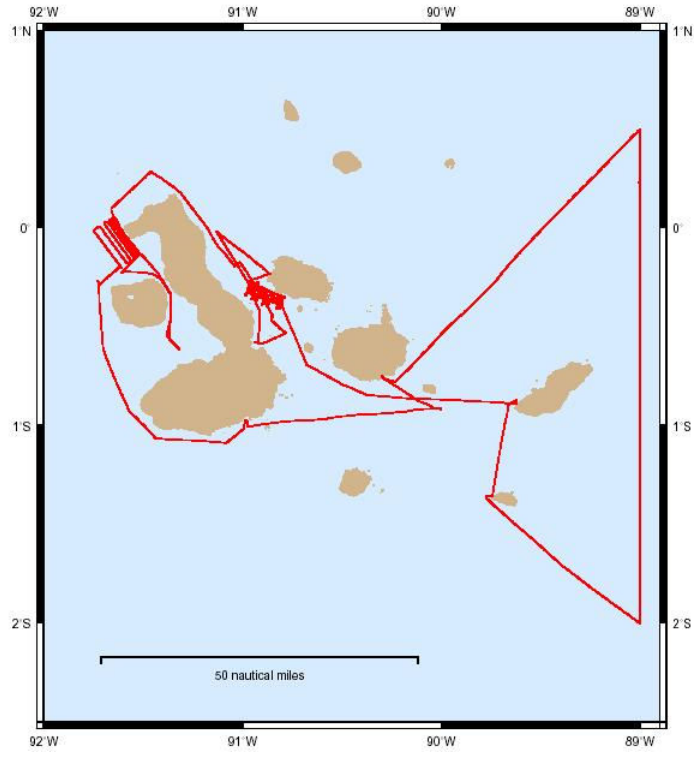
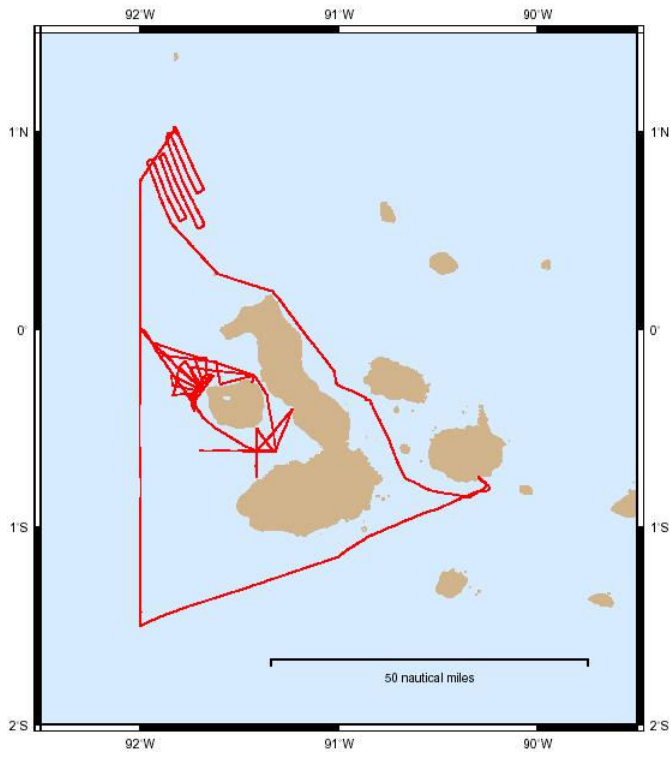


Figure 2: Schematic EUC Terminal Flows

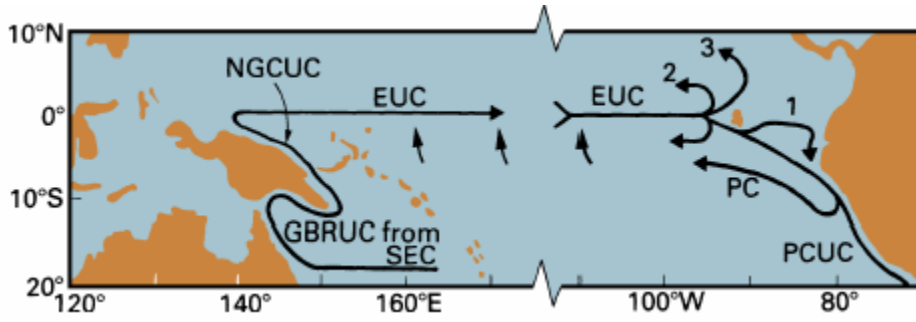


Figure 3 92°W ADCP Transects Only

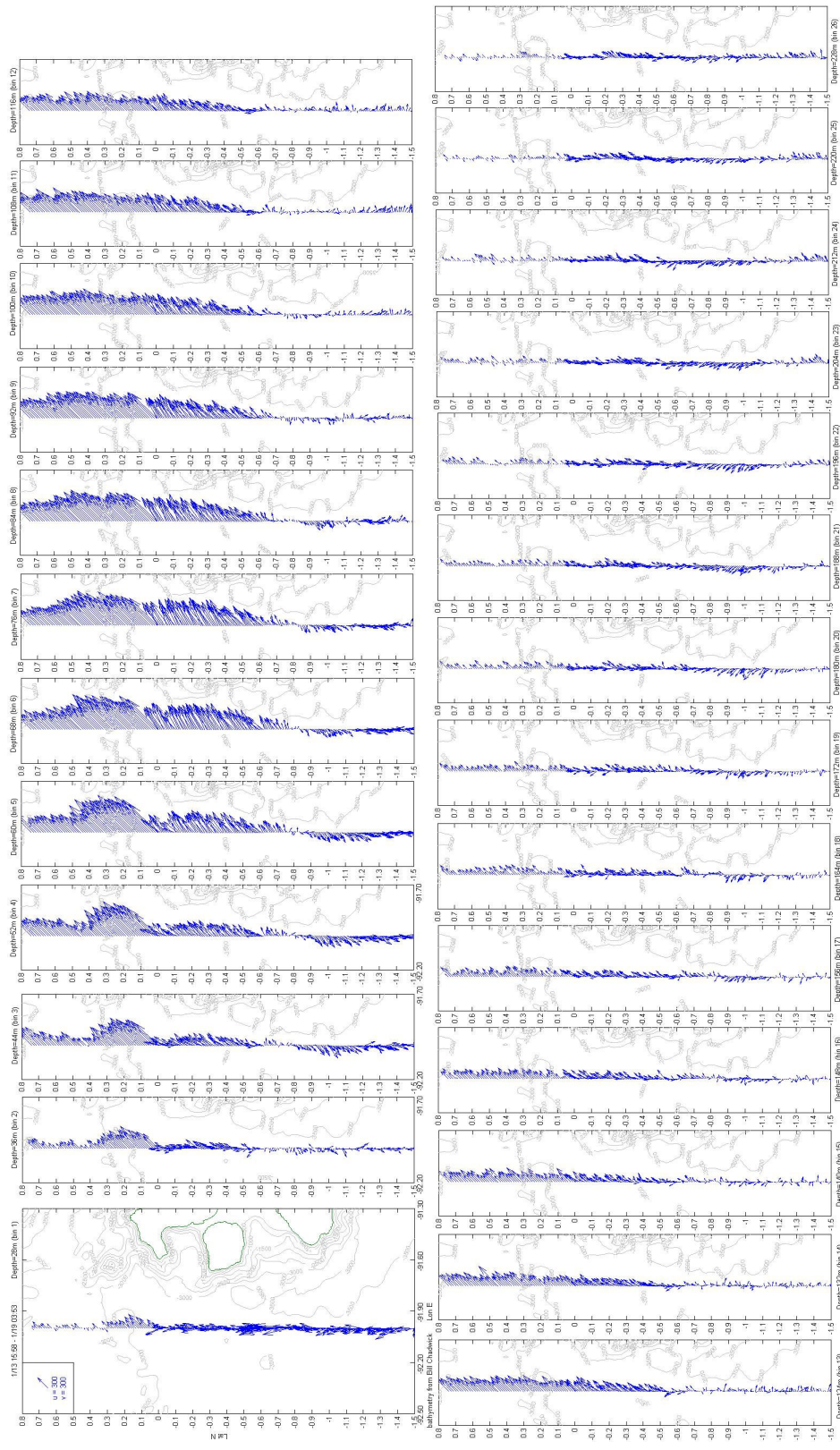


Figure 4 92°W ADCP with Coastal ADCP Transects

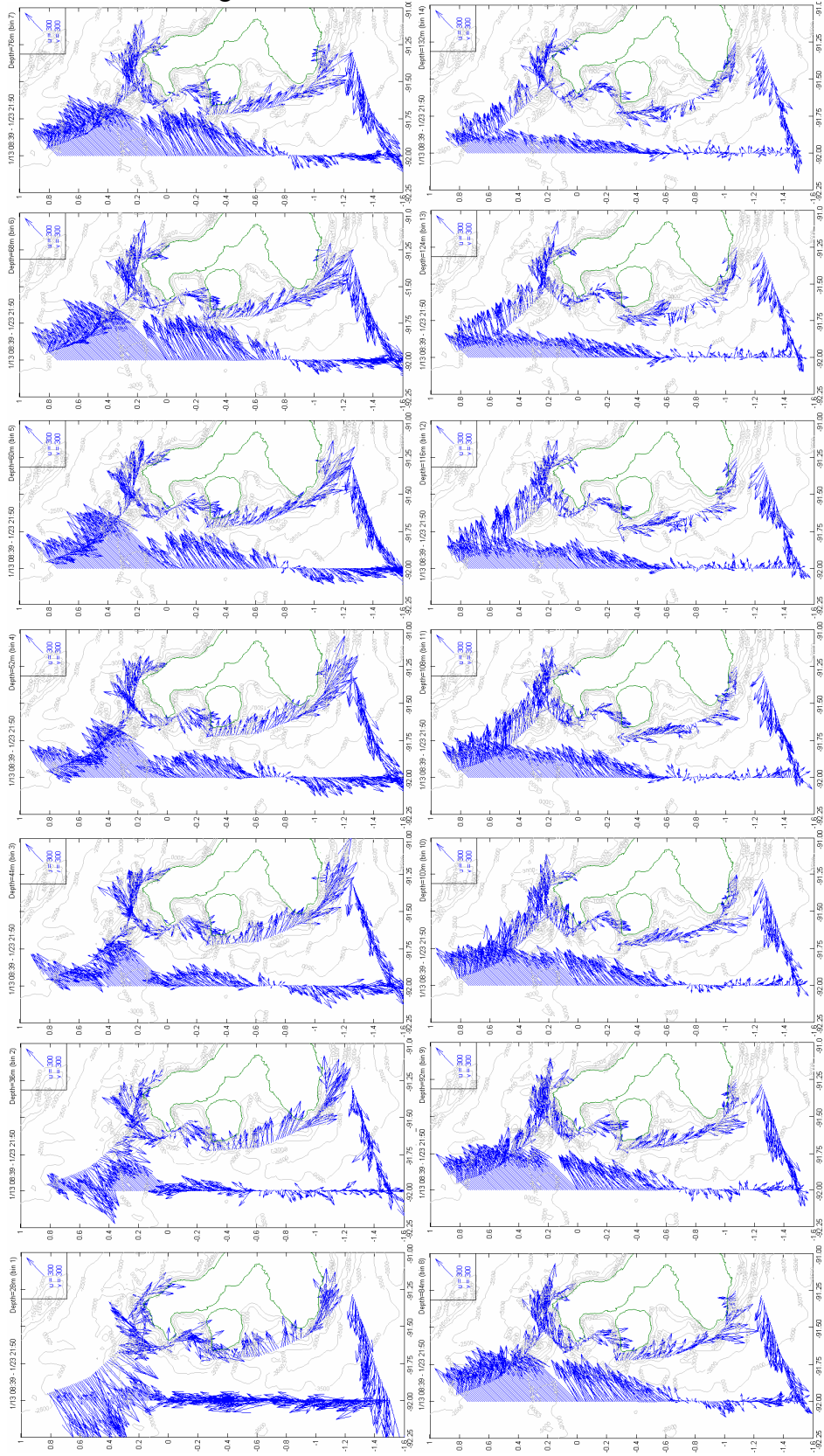
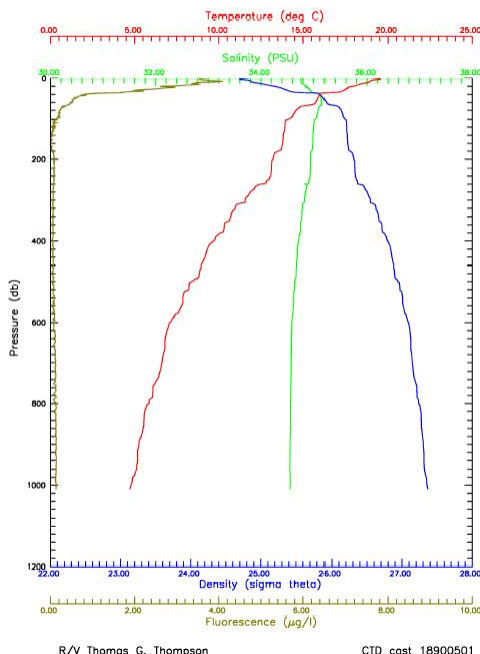


Figure 5 CTD EUC confirmation using casts 501 and 601

Cruise Information		Station Information		Instrumentation					
Ship Name:	R/V Thomas G. Thompson	Station Name:	80-3798-3	CTD Type:	SBE 911+				
Cruise Name:	Galapagos	Station Number:	Station 5	Configuration:	CC, TT, FL, Tr, O2, Alt				
Cruise Number:	18189	Cast Number:	14	Water Depth (Meters):	2453.4				
Observer's Name:	Hagg / Realaender	GMT Date:	14/01/06	Data Filename:	18900501.DAT				
GMT Start:	00:37:11	GMT Finish:	01:37:44	Audio Tape Number:					
Latitude Start:	S 00 36.9894	Latitude Finish:	S 00 37.0014	Audio Tape Start:					
Longitude Start:	W 091 59.9910	Longitude Finish:	W 091 59.9980	Audio Tape Finish:					
CTD Data									
Bottle Position	Serial No.	Depth (Meters)	Pressure (db)	Temp1 (Deg C)	Temp2 (Deg C)	Cond1 (ms/cm)	Cond2 (ms/cm)	Salinity1 (PSU)	Salinity2 (PSU)
1	108041	1001.4	1009.4	4.695	4.699	23.250	33.252	34.559	34.559
2	108055	1001.8	1009.8	4.695	4.697	23.250	33.251	34.559	34.559
3	108071	501.9	505.3	8.222	8.233	26.310	36.320	34.642	34.642
4	108042	502.3	505.6	8.225	8.243	26.313	36.330	34.643	34.642
5	108073	303.8	305.7	11.150	11.157	39.126	39.132	34.805	34.805
6	108062	303.3	305.2	11.196	11.207	39.173	39.182	34.810	34.809
7	108063	253.2	254.7	12.809	12.783	40.795	40.768	34.907	34.904
8	108060	253.5	255.0	12.809	12.801	40.795	40.798	34.906	34.907
9	108069	253.3	254.8	12.810	12.770	40.797	40.757	34.907	34.905
10	108067	202.2	203.4	13.183	13.179	41.171	41.168	34.941	34.942
11	108052	153.5	154.3	13.819	13.813	41.816	41.810	34.987	34.987
12	108045	154.0	154.9	13.823	13.824	41.820	41.822	34.987	34.987
13	108054	103.2	103.7	14.146	14.142	42.166	42.162	35.036	35.036
14	108046	77.9	78.3	14.720	14.699	42.708	42.765	35.101	35.099
15	108079	53.4	53.6	15.843	15.850	43.935	43.941	35.145	35.144
16	108048	43.6	43.8	15.928	15.915	44.006	43.995	35.137	35.138
17	108074	33.6	33.7	16.318	16.410	44.318	44.395	35.074	35.061
18	108078	28.9	29.0	17.317	17.332	45.158	45.176	34.940	34.942
19	108088	24.1	24.2	17.529	17.532	45.323	45.329	34.902	34.904
20	108066	13.6	13.6	18.175	18.168	45.879	45.872	34.829	34.829
21	108072	13.7	13.7	18.159	18.154	45.868	45.865	34.832	34.835
22	108068	13.7	13.7	18.163	18.171	45.872	45.879	34.833	34.832
23	108051	2.4	2.4	18.956	19.355	46.587	46.982	34.769	34.765
24	108065	2.2	2.2	18.926	19.022	46.555	46.655	34.768	34.771



Cruise Information		Station Information		Instrumentation					
Ship Name:	R/V Thomas G. Thompson	Station Name:	80-4	CTD Type:	SBE 911+				
Cruise Name:	Galapagos	Station Number:	Station 6	Configuration:	CC, TT, FL, Tr, O2, Alt				
Cruise Number:	18189	Cast Number:	14	Water Depth (Meters):	2103.1				
Observer's Name:	Hagg / Realaender	GMT Date:	14/01/06	Data Filename:	18900601.DAT				
GMT Start:	09:03:08	GMT Finish:	09:31:18	Audio Tape Number:					
Latitude Start:	N 00 00.0120	Latitude Finish:	N 00 00.0099	Audio Tape Start:					
Longitude Start:	W 091 59.9801	Longitude Finish:	W 091 59.9714	Audio Tape Finish:					
CTD Data									
Bottle Position	Serial No.	Depth (Meters)	Pressure (db)	Temp1 (Deg C)	Temp2 (Deg C)	Cond1 (ms/cm)	Cond2 (ms/cm)	Salinity1 (PSU)	Salinity2 (PSU)
1	108041	302.4	304.3	10.927	10.926	28.896	38.895	34.789	34.785
2	108055	302.4	304.3	10.927	10.928	28.896	38.897	34.789	34.785
3	108071	203.5	204.7	13.866	13.867	41.883	41.884	34.986	34.986
4	108042	203.1	204.3	13.865	13.867	41.883	41.885	34.987	34.986
5	108073	151.9	152.7	13.923	13.924	41.921	41.921	34.991	34.990
6	108062	151.9	152.7	13.924	13.919	41.922	41.917	34.991	34.990
7	108063	101.9	102.5	14.308	14.310	42.286	42.287	35.000	35.000
8	108060	101.1	101.6	14.310	14.311	42.286	42.287	35.000	35.000
9	108069	76.4	76.8	14.596	14.609	42.500	42.513	34.950	34.945
10	108067	77.0	77.4	14.572	14.593	42.476	42.499	34.949	34.950
11	108052	53.0	53.2	16.359	16.364	44.361	44.364	35.067	35.067
12	108045	52.7	52.9	16.359	16.371	44.361	44.373	35.068	35.068
13	108054	43.8	44.0	16.746	16.727	44.701	44.687	35.032	35.031
14	108046	43.1	43.3	16.741	16.741	44.697	44.697	35.033	35.033
15	108079	34.1	34.2	16.841	16.838	44.763	44.762	35.007	35.006
16	108048	34.2	34.3	16.831	16.843	44.756	44.766	35.010	35.001
17	108074	23.2	23.3	17.360	17.277	45.206	45.132	34.945	34.953
18	108078	23.2	23.3	17.363	17.340	45.209	45.185	34.946	34.945
19	108088	13.5	13.5	17.426	17.442	45.255	45.269	34.935	34.934
20	108066	13.7	13.7	17.476	17.449	45.296	45.276	34.927	34.933
21	108072	2.8	2.8	19.554	19.852	47.203	47.513	34.782	34.790
22	108068	2.8	2.7	20.199	20.204	47.846	47.852	34.775	34.774
23									
24									

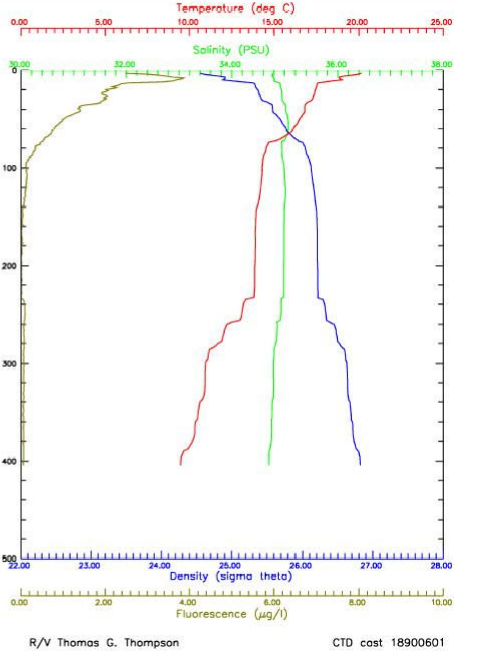


Figure 7 Satellite SST and Chlorophyll

